The Relation Between Gas Density and Star Formation Rate in the Spiral Galaxy M100

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Overview

The DS9 astronomical image viewing tool will be used to examine the relation between the rate at which stars are forming and the interstellar molecular gas used to create those stars in the spiral galaxy M100. An image of the 2.6 mm spectral line emission from carbon monoxide within the interstellar molecular gas will be used to measure molecular gas mass. Images of ultraviolet (226.7 nm) light from hot young stars and mid-infrared (24μm) light from interstellar dust in star forming regions will be used to determine the star formation rate. With measurements of these quantities from multiple regions within the galaxy, it will be possible to show the relation between gas mass and star formation rate.

General Astronomy Concepts

Stars form out of interstellar molecular gas. The rate at which stars form is directly proportional to the amount of molecular gas that is available to make those stars. This is named the Kennicutt-Schmidt relation after the two people who first studied it. To show the relation exists, it is necessary to make measurements that can be used to calculate the mass of molecular gas present and the rate at which stars are forming.
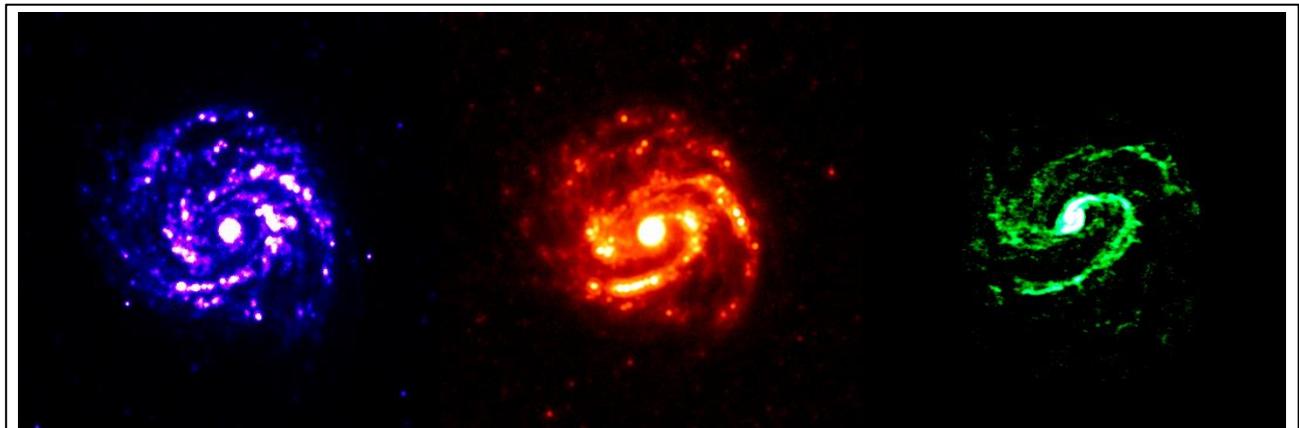

Figure 1: Three images of M100. The left image shows the near-ultraviolet (226.7 nm) emission from hot young stars in star forming regions[1]. The middle image shows the mid-infrared (24 μm) emission from interstellar dust in the star forming regions[2]. The right image shows the 2.6 mm emission from carbon monoxide within the interstellar molecular gas from which stars form.

The primary molecule found in interstellar molecular gas is the hydrogen molecule (H_2), which contains two hydrogen atoms. Because it is symmetric, it does not produce spectral line emission very easily, so it is not possible to identify molecular gas clouds in space by looking for molecular hydrogen spectral lines. The next most common molecule in the interstellar medium is carbon monoxide (CO). This produces multiple spectral lines that can be seen at millimetre and submillimetre wavelengths, and the amount of spectral line emission can be directly related to the density of the interstellar gas. The right-side panel in Figure 1 shows the image of CO spectral line emission at 2.6 mm (115 GHz) that will be used in this experiment. The image was produced by the Atacama Large Millimeter/submillimeter Array (ALMA).

When a group of stars form out of interstellar gas, the stars have a range of luminosities (the total energy radiated per unit time) and colours that follow a relation called the main sequence, which appears as a diagonal line from the upper left to lower right in Figure 2. The most luminous stars are also the bluest, the
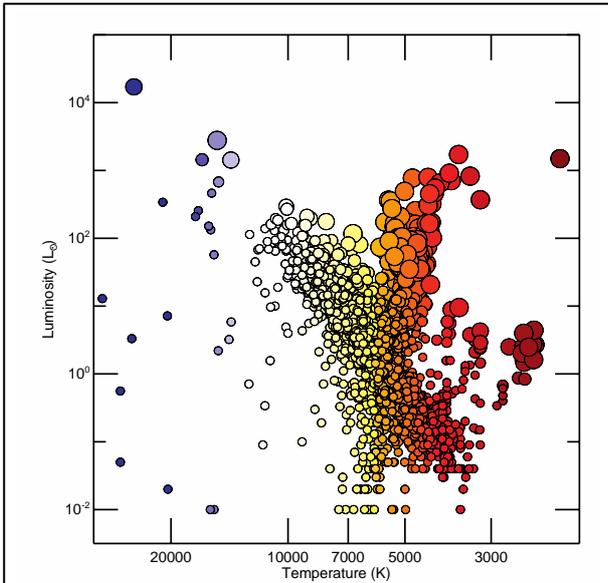
Figure 2: Plot of stellar luminosity versus stellar temperature for all stars within 250 light years of Earth based on a re-analysis of data from the Hipparcos satellite[3].

hottest, and the most massive. They also have very short lifespans; the largest only stay on the main sequence for a few million years before running out of hydrogen in their cores, which causes them to undergo a series of changes in which they first become red supergiant stars and then supernovae.

Since the blue main sequence stars have short lifespans, astronomers typically look for them to identify where stars are forming. While it is easy to identify individual blue stars within our Galaxy, it is difficult to separate the blue stars from the other stars in most other galaxies, even using the Hubble Space Telescope. Instead, astronomers look for signs that many hot young stars are present.

One of the ways to identify where stars are forming in other galaxies is to look for ultraviolet light, which is primarily produced by the hottest, bluest stars. The left-side panel in Figure 1 shows the ultraviolet (226.7 nm) image used for this experiment. This image comes from the Galaxy Evolution Explorer

However, some of the ultraviolet light from these hot young stars does not escape the gas clouds that these stars formed from. Instead, the light is absorbed by interstellar dust. The dust then heats up to temperatures above 100 K and produces mid-infrared emission at wavelengths of 5-30 μm. While this means that the ultraviolet emission itself may not be directly related to the rate at which stars are forming, it is possible to use measurements of the infrared emission to correct measurements of the ultraviolet emission to account for the fraction of the light that was absorbed by interstellar dust. The mid-infrared (24 μm) image from the Spitzer Space Telescope that is used in this experiment is shown in the centre panel of Figure 1.

M100 is a well-studied face-on spiral galaxy where millimetre spectral line data, ultraviolet data, and mid-infrared data are all publicly available. By measuring the emission in these bands from multiple subregions within M100, it is possible to calculate star formation rates and corresponding molecular gas masses. These data can then be used to recreate the Kennicutt-Schmidt relation for this specific galaxy.

Additional Information: Units for Measuring Light

The analysis in this experiment is based on data with units of Janskys (Jy). One Jy is equal to 10^{-26} W/m^2/Hz. This is a measurement of a quantity referred to as flux density (f_v), which represents the amount of energy (ΔE) per time (Δt) observed within a given frequency range (Δv) that can be collected over a telescope area (ΔA), or

$$f_v = \frac{\Delta E}{\Delta t\ \Delta A\ \Delta v}$$

Sometimes measurements are reported as surface brightness (I_v), which is the flux density spread over an area of the sky ($\Delta \Omega$). This is given by the equation

$$I_v = \frac{f_v}{\Delta \Omega} = \frac{\Delta E}{\Delta t\ \Delta A\ \Delta v\ \Delta \Omega}$$
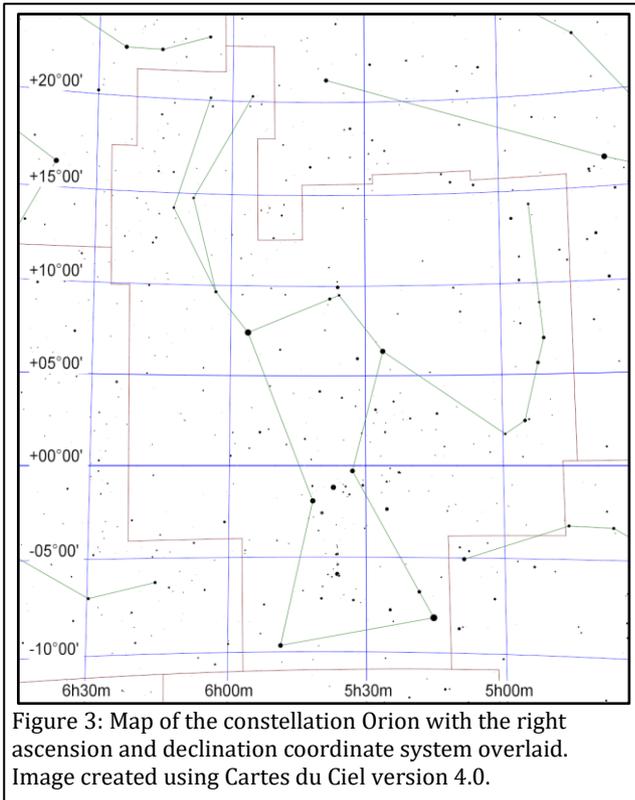
Figure 3: Map of the constellation Orion with the right ascension and declination coordinate system overlaid. Image created using Cartes du Ciel version 4.0.

Additional Information: Coordinate Systems

Astronomers use a coordinate system similar to the latitude and longitude system applied to Earth. The astronomical equivalent coordinates are called right ascension and declination. Right ascension is equivalent to longitude, and it is often measured in hours, minutes, and seconds with a range from 0 to 24 hours, with 60 minutes in an hour, and with 60 seconds in a minute. Sometimes, however, right ascension is measured in degrees instead (with 1 hour equivalent to 15 degrees). Declination is equivalent to latitude, and it is measured in degrees, minutes, and seconds, with 60 minutes in a degree and 60 seconds in a minute. Declination ranges from +90:00:00 (at the point directly above the Earth's North Pole) through 00:00:00 (the location directly above the Earth's equator) to -90:00:00 (at the point directly above the Earth's South Pole). See Figure 3 for an example of this coordinate system overlaid on the constellation Orion.

Lengths and distances in the sky are often measured in degrees, arcminutes, and arcseconds, with 60 arcminutes in 1 degree and 60 arcseconds in 1 arcminute. For reference, the Sun and Moon are both 0.5 degrees (or 30 arcminutes) across. The Andromeda Galaxy, which is the nearest spiral galaxy, and the Pleiades cluster of stars are both 3 degrees across.

Areas are often described as square versions of the angular measurements, such as square degrees (deg^2), square arcseconds ($arcsec^2$), and square radians or steradians (sr). Areas in radio data are often described in terms of the beam of telescope, which is the angular area that light from a point source is spread over in the final images. The ALMA data used in this experiment have a beam area of 10.78 $arcsec^2$.

Preparation Procedure

1. Download and install DS9 from the DS9 download page (https://sites.google.com/cfa.harvard.edu/saoimageds9/download). This software is available for Windows, Mac, and Linux.

2. Download the ALMA data, which imaged the CO spectral line emission, from https://bulk.cv.nrao.edu/almadata/sciver/M100Band3ACA/M100_Band3_DataComb_ReferenceImages_5.1.tgz . If that does not work, go to https://bulk.cv.nrao.edu/almadata/sciver/M100Band3ACA/ and download the file M100_Band3_DataComb_ReferenceImages_5.1.tgz. This is a compressed file format called a gzipped tar file.

3. Follow one of the procedures below to extract the image from the tgz file.
    a. On Windows computers, use either PeaZip (http://www.peazip.org/) or 7-Zip (http://www.7-zip.org/) to first extract the tar file from the gzipped tar file and then the extract the data files from the tar file. In the resulting folder, file the file named M100_Feather_CO.image.mom0.pbcor.fits and copy this to a new folder for analysis files.
    b. On Mac computers, double-click on the downloaded tgz file to open it. Find the file named M100_Feather_CO.image.mom0.pbcor.fits and copy this to a new folder for analysis files.
    c. On Linux computers, open a console and go to the directory where the tgz file is located. Use the command "tar –xzf M100_Band3_DataComb_ReferenceImages_5.1.tgz" to extract the files.

In the resulting folder, find the file named " M100_Feather_CO.image.mom0.pbcor.fits" and move it to a new directory for the analysis files.

4. Download the following images from the NASA/IPAC Extragalactic Database (NED), a general astronomy image and data repository at http://ned.ipac.caltech.edu/ .
    a. Download the GALEX near-ultraviolet image from http://ned.ipac.caltech.edu/uri/NED::Image/fits/2014ApJS..212...18B/NGC_4321_GALEX_NUV:bms2014 . If the downloaded image does not end in ".fits", add this to the end of the filename. Move this to the same folder as M100_Feather_CO.image.mom0.pbcor.fits.
    b. Download the Spitzer mid-infrared image from http://ned.ipac.caltech.edu/uri/NED::Image/fits/2012MNRAS.423..197B/NGC_4321:I:MIPS24:bgm2012 . If the downloaded image does not end in ".fits", add this to the end of the filename. Move this to the same folder as M100_Feather_CO.image.mom0.pbcor.fits.

Measurement Procedure

1. Start DS9.

2. Under "File" in either the menu or the button bar, click on "Open" and then open the CO spectral line image (M100_Feather_CO.image.mom0.pbcor.fits).

3. Under "Scale", click on "log". This will change the way that the image values are displayed on the computer screen.

4. If it is necessary to change the brightness and contrast of the image to see the galaxy better, first move the cursor to the image window, then hold down the right mouse button (or, on a Mac laptop, hold down the mouse button and the cmd key at the same time), and then move the cursor either up and down or side to side in the window. Do this until both spiral arms are visible but without making them look completely white. The result should look similar to Figure 4.
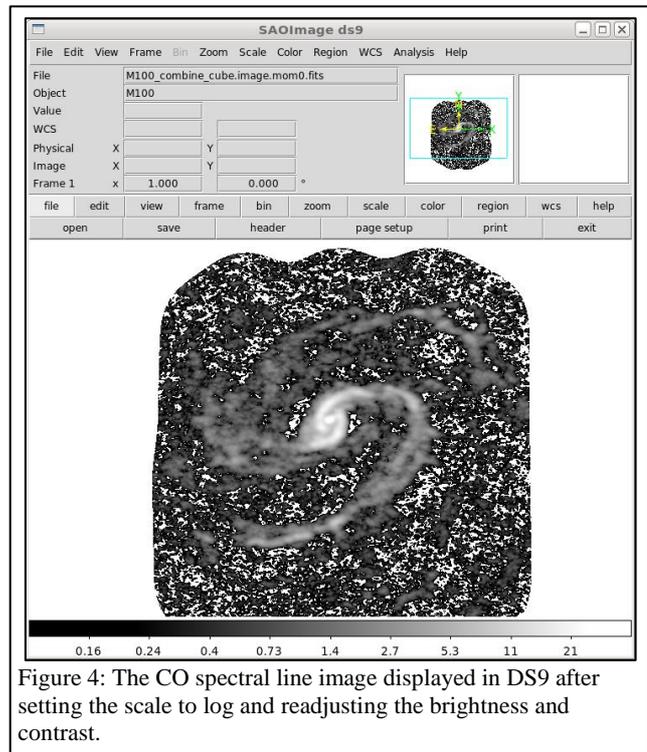

Figure 4: The CO spectral line image displayed in DS9 after setting the scale to log and readjusting the brightness and contrast.

5. As an additional option, change the colours by clicking on an alternate scheme under "Color" in the menu or button bar. (It may be necessary to repeat step 4 after doing this.)

6. To zoom in or out, either use the scroll wheel on the mouse or go to "Zoom" in the menu or button bar and select one of the options.

7. Under "Edit" in either the menu or button bar, click on "pointer" or, if that is not listed, "region".

8. Left click on the image to draw a circle. Move the circle so that it is centred on a bright source, preferably a point-like source or a bright segment of one of the spiral arms. See Figure 5 for an example.

9. Double-click on the circle, which will open a new window. Set the coordinates of the centre of the circle to "fk5", and make sure that "WCS" in the drop-down menu has a check mark next to it. After doing this, record the coordinates of the circle. Set the units of the circle radius to "arcsec", and make sure

that "WCS" in the drop-down menu has a check mark next to it. After this, set the radius of the circle to 10 arcseconds.

10. Under "Analysis" in the menu for the Circle window, click on "Statistics". This will open a new window. Record the number listed under sum as the CO spectral line emission. Also record the number of pixels in the region.

11. Repeat steps 8-10 to measure the emission from at least 20 regions within the galaxy that have the same size and that cover CO spectral line emission. Draw a new region each time rather than moving the existing region.

12. Under "Region" in either the menu or button bar of the main DS9 window, click on "Save Regions". In the next dialog window that appears, give the region file a name and click "Save". In the second dialog window that appears, make sure that the format is set to "ds9" and the coordinate system is set to "fk5" and click "OK".
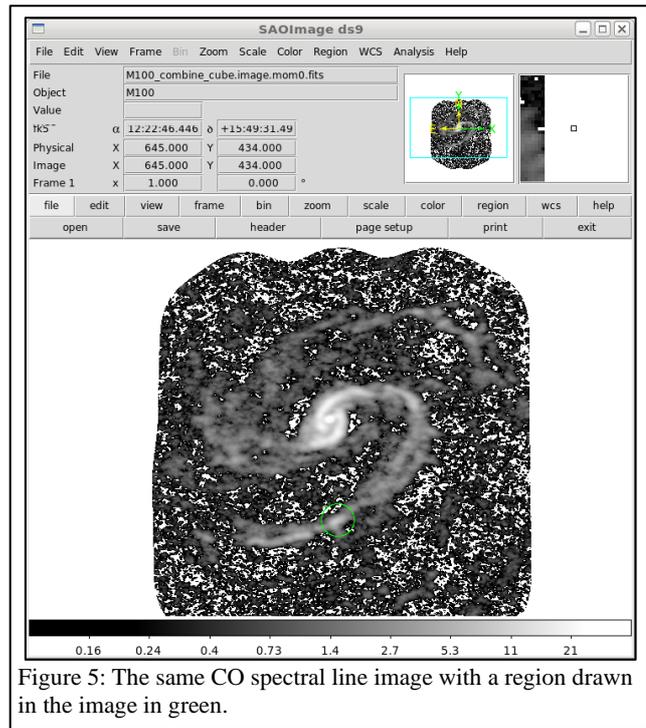

Figure 5: The same CO spectral line image with a region drawn in the image in green.

13. Once the regions are saved, click on "Delete All Regions" under "Region".

14. Repeat steps 8-9 to create 10 regions in locations with no obvious emission. Set the radius of each region to 10 arcsec. These regions will be treated as representing the background. For each region, open the statistics window and record the standard deviation of the pixel values (not the value under "error", which incorrectly assumes the statistics are Poissonian). Once all 10 regions have been created, repeat step 12 to save the regions.

15. Repeat steps 2-6 to open and display the mid-infrared image (NGC_4321:I:MIPS24:bgm2012.fits).

16. Under "Region", click on "Load Regions". Load the target region file that was saved in step 12. (If a dialogue box appears, just click "OK".) After this, repeat step 10 to measure the mid-infrared emission from each target region and the number of pixels in each region. Record the mid-infrared datat for each region next to the corresponding CO line data for the region.

17. Delete all the regions, and then repeat steps 8-9 to create 10 regions in locations with no obvious emission. (Do not use the same background regions created for the CO image.) For each region, open the statistics window and record the standard deviation. Then repeat step 12 to save the regions.

18. Repeat steps 2-6 to open and display the near-ultraviolet image (NGC_4321_GALEX_NUV:bms2014.fits).

19. Under "Region", click on "Load Regions". Load the target region file that was saved in step 12. Repeat step 10 to measure the near-ultraviolet emission from each target region. Record the near-ultraviolet data for each region next to the corresponding CO line and mid-infrared data for the region.

20. Delete all the regions, and then repeat steps 8-9 to create 10 regions in locations with no obvious emission. (Do not use the same background regions created for the CO or mid-infrared images.) For each region, open the statistics window and record the mean value and standard deviation. Then repeat step 12 to save the regions.

Numerical Analysis Procedure

1. For the near-ultraviolet image, calculate the mean of the measurements within the background regions. Then, for each target region in the near-ultraviolet image, subtract the average background value.

2. For each image, calculate the average of the standard deviation measurements from the background regions. Use this number and the number of pixels in each target region to calculate the uncertainties for each measurement from each target region.

3. The GALEX near-ultraviolet data units are counts per second. Convert the measurements and uncertainties to Janskys (Jy) by multiplying them by 3.365×10^{-5} Jy/(counts/s).

4. The GALEX data have a calibration uncertainty of 3% [5]. Combine these uncertainties with the uncertainties based on the background noise.

5. The Spitzer mid-infrared data image units are in megaJanskys per steradian (MJy/sr). The measurements and uncertainties from this image should be converted to Jansky/arcsec^2 by multiplying by 2.35×10^{-5} (Jy/arcsec^2)/(MJy/sr). After this, the numbers should be converted to Janskys by multiplying by the pixel area, which is 2.25 arcsec^2.

6. The Spitzer 24 µm image has a calibration uncertainty of 4% [6]. Combine these uncertainties with the uncertainties based on the background noise.

7. Star formation rates are usually expressed in units of solar masses formed per year, or $M_\odot$/yr. One solar mass is equivalent to the mass of the Sun, or 1.99×10^{30} kg. The star formation rate (*SFR*) for the individual regions can be calculated in $M_\odot$/yr using

$$SFR = \left[0.106 \frac{M_\odot/\text{yr}}{\text{Jy Mpc}^2} \right] [f_\nu(NUV) + 0.0213 f_\nu(MIR)] D^2.$$

This is a simplified version of multiple other conversion equations[4] where $f_\nu(NUV)$ is the near-ultraviolet flux density in Janskys, $f_\nu(MIR)$ is the mid-infrared flux density in Janskys, and D is the distance in megaparsecs. Megaparsecs are commonly used to measure distances to galaxies; 1 megaparsec is equal to 10^6 parsecs and 1 parsec is equal to 3.26 light years. The distance to M100 is 15.2 Mpc[7].

8. The ALMA data have a calibration uncertainty of 3% [8]. Combine these uncertainties with the uncertainties based on the background noise.

9. The ALMA CO spectral line data are in units of Jy/beam km/s, an alternate measurement of the amount of electromagnetic radiation observed per angular area on the sky. Convert the CO measurements and uncertainties to Jy/arcsec^2 km/s by dividing by the beam area (10.78 arcsec^2). Next, convert the data to Jy km/s by multiplying by the pixel area, which is 0.25 arcsec^2.

10. Calculate the molecular gas mass ($M_{Mol\ Gas}$) in solar masses using

$$M_{Mol\ Gas} = \left[7860 \frac{M_\odot}{\text{Jy km/s Mpc}^2} \right] I D^2$$

where I is the measurement from the CO spectral line image in Jy km/s and D is the distance in megaparsecs. This equation is a simplified version based on conversion equations from two references[9,10].

11. Calculate the base-10 logarithms of the star formation mass and the molecular gas mass. After doing this, create a plot with the logarithm of the molecular gas mass for each region on the x-axis and the corresponding logarithm of the star formation mass for each region on the y-axis. This is the final result of this experiment.

Discussion Questions

1. When viewing the near-ultraviolet and mid-infrared images, how do they look similar? How do they look different? Are any regions visible in the near-ultraviolet image that are not seen in the mid-infrared image or vice-versa?

2. When viewing the CO spectral line image, how does it look similar to the near-ultraviolet and mid-infrared images? How does it look different?

3. In the plot of star formation rate versus molecular gas mass, do the data look like they follow a linear relation?
   a. If they are not related, is there anything about the appearance of the images that indicates why they appear unrelated?
   b. If most of the data follow a linear relation but one of the data points does not fall on the relation, try to identify what is special about the region where that measurement was made.

4. What is the greatest source of uncertainty in the data? Is it the background noise or the calibration uncertainty? Do the relative contributions of these two sources of uncertainty vary across the image?

5. For both bright and faint regions in each image, how does the size of the measurement aperture affect the signal-to-noise ratio? In which situations would a narrower region be preferable? In which situations would a wider region be preferable?

References

[1] Brown M. J. I. et al., *An Atlas of Galaxy Spectral Energy Distributions from the Ultraviolet to the Mid-infrared*, 2014, *Astrophysical Journal Supplement Series*, 212, 18

[2] Bendo G. J. et al., *MIPS 24-160 μm photometry for the Herschel-SPIRE Local Galaxies Guaranteed Time Programs*, 2012, *Monthly Notices of the Royal Astronomical Society*, 423, 167

[3] McDonald I. et al., *Fundamental parameters and infrared excesses of Hipparcos stars*, 2012, *Monthly Notices of the Royal Astronomical Society*, 427, 343

[4] Kennicutt R. C., Evans N. J., *Star Formation in the Milky Way and Nearby Galaxies*, 2012, *Annual Reviews of Astronomy & Astrophysics*, 50, 531

[5] Morrissey P. et al., *The Calibration and Data Products of* GALEX, 2007, *Astrophysical Journal Supplement Series*, 173, 682

[6] Engelbracht C. W. et al., *Absolute Calibration and Characterization of the Multiband Imaging Photometer for Spitzer. I. The Stellar Calibrator Sample and the 24 μm Calibration*, 2007, *Publications of the Astronomical Society of the Pacific*, 119, 859

[7] Freedman W. L. et al., *Final Results from the Hubble Space Telescope Key Project to Measure the Hubble Constant*, 2001, *Astrophysical Journal*, 553, 47

[8] Warmels R. and Remijan T., eds., *ALMA Cycle 5 Technical Handbook*, 2017. Joint ALMA Observatory, Santiago, Chile

[9] Kenney J. D. P., Young J. S., *The effects of environment on the molecular and atomic gas properties of large Virgo cluster spirals*, 1989, *Astrophysical Journal*, 344, 171

[10] Bolatto A. D., Wolfire M., Leroy A. K., 2013, *The CO-to-H_2 Conversion Factor*, *Annual Reviews of Astronomy & Astrophysics*, 51, 207